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Creating an artificial Geminid meteor shower: Correlation between ejecta velocity and observability

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Abstract

One of the interesting arguments for a space impact mission to asteroid 3200 Phaethon is to create an artificial Geminid meteor shower. In this work we investigate the artificial shower's dates of observability and dependence on ejecta velocity using dust trail theory. We find that when the dust ejecta velocities are 200 m/s the artificial meteor showers start to be visible in 2204 and continue for about 30 years. If the dust ejecta velocity is 20 m/s they only last 10 years from 2215 to 2225. Thus, the onset of artificial shower activity begins sooner and lasts longer with higher ejecta velocities. To produce an artificial meteor shower with 3200 Phaethon as the parent will require higher impact energy than the Deep Impact spacecraft delivered to 9P/Tempel 1.

Keywords: Artificial meteor shower; Deep Impact

1. Introduction

Ground-based observations suggest that the surfaces of primitive objects such as comets, asteroids, and dormant comets have probably been modified physically and compositionally by solar heating and/or space weathering (e.g. Jewitt, 2004). However, their interiors have probably been unaffected by these processes. Therefore, Belton and A'Hearn (1999) proposed a scientific mission to explore the sub-surface region using excavation in a hypervelocity impact. The existence of relatively pristine materials is expected at depths of about 20 m.

The Deep Impact (DI) mission revealed differences between the surface and interior comet 9P/Tempel 1 (A'Hearn et al., 2005). The DI collision excavated relatively unprocessed cometary material from tens of meters below the comet's surface. A world-wide observational campaign using ground and space-based telescopes (Meech et al., 2005) monitored the comet before and after the impact. Sugita et al. (2005) carried out mid-IR spectroscopic observations and derived a crystalline-to-amorphous ratio of silicates for the ejected dust. The ratio is similar to those of Oort-cloud comets (e.g. Hale-Bopp) and suggest that Jupiter-family comets and Oort-cloud comets have a similar origin.

Kasuga et al. (2006b) proposed the DI concept for a space mission to a meteor shower parent body. The target is asteroid 3200 Phaethon which has been recognized as the parent of the Geminid meteor stream and it has been suggested that the asteroid is actually a dormant comet. On the basis of dust trail theory (e.g. McNaught and Asher, 2002) a DI-like collision on 3200 Phaethon will be able to cause an artificial meteor shower a couple hundreds years after the impact event if we took ejecta velocities of 20 m/s, which are almost consistent with the orbital evolution of that parent. The onset of activity for the artificial meteor shower will depend on the velocity of ejected dust.

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Table 1
Derived ejecta velocities due to the DI Impactor's collision with 9P/Tempel 1 as determined from ground-based telescopes

Observation	Ejecta velocity (m/s)	Reference
Optical (mid-IR)	~200 ± 20	Meech et al. (2005)
Optical (orange filter 648 ± 43 nm)	>160	Keller et al. (2005)
Optical (orange filter 648 ± 43 nm)	110–300	Küppers et al. (2005)
Spectroscopy (mid-IR)	125 ± 10	Sugita et al. (2005)
Optical (VR–BV filters)	230	Schleicher et al. (2006)
Polarimetry	158–270	Furusho et al. (submitted for publication)

In this paper we model a DI-like collision on 3200 Phaethon on 2022 April 12. The selected impact date was chosen because the object passes through the ecliptic plane on the Earth side and a new mission program can be carried out in Japan (Kasuga et al., 2006b) after 2020. We use the derived ejected velocities of dust plume during DI impact on 9P/Tempel 1 from ground-based observations in our simulations. We calculate the distributions of a tube of the dust trail for artificial meteor showers activated in the impact and discuss the observable duration of artificial meteor shower.

2. Simulation of the artificial meteor shower

Table 1 compiles several observational methods using ground-based telescopes during the DI collision on 9P/Tempel 1 along with derived velocities of the ejected dust plume (Meech et al., 2005; Keller et al., 2005; Küppers et al., 2005; Sugita et al., 2005; Schleicher et al., 2006; Furusho et al., submitted for publication). They were obtained 6–23 h later or throughout the impact time on UT 4 July 2005. The derived velocities of ejected dust range from about 100 to 300 m/s.

We simulated the evolution of a tube of the dust trail associated with a DI-like collision on 3200 Phaethon using the most simple dust trail theory (Sato, 2003). Radiation pressure can be neglected because Kasuga et al. (2006a) clarified that meteoroids in showers are large and compact: blackbody-like particles rather than sub-micron and fluff balls (Kimura et al., 2002). The meteoroids must be large because of their small β values[1] of 10^{-5} to 10^{-3}, which are obtained from observations of cometary dust trails (Ishiguro et al., 2002, 2003).

We selected the impact day on 3200 Phaethon as 2022 April 12 and assume that the ejected dust particles are moderately large and compact. We assumed the ejecta velocity to be 200 m/s – almost averaged value from Table 1 and it would have stable dust ejecta with the negligible gas ejection force. The 200 m/s ejection velocity used in the simulation is roughly at the upper limit for micron sized dust particles because the DI results for 9P/Tempel 1 were obtained with optical to mid-IR telescopes (e.g. Meech et al., 2005). We expect that larger dust particles will have slower ejection velocities.

A'Hearn et al. (2005) reported the fastest ejecta velocity of ~5 km/s immediately after the impact flash using the *in situ* flyby camera on the DI spacecraft. That material was accompanied by a gas-driven expansion so the velocity value deduced by A'Hearn is appropriate to active comets in the production of artificial meteor showers.

2.1. Results: fast ejecta velocity of 200 m/s

Details of the simulation process are described in Sato (2003) and Kasuga et al. (2006b). In general, we consider the short term evolution of Phaethon's orbital elements (for about hundred years). Then we determine the distribution of a tube of the dust trail formed at the collision epoch using test meteoroids ejected in the direction of Phaethon's motion (which we define as positive ejection velocities) and in the opposite direction (negative ejection velocities). The orbital evolution of Phaethon and the test meteoroids are roughly constant because their orbits are far from Jupiter.

Fig. 1 shows the evolution of a tube of the dust trail after the impact event on 2022 April 12 where the ejecta velocities ranged from −200 to +200 m/s. The artificial meteor shower would be observable on the Earth for about 30 years from about 2204 to 2236. The earliest showers are those caused by dust trails formed of mainly +200 m/s ejecta while for the latest showers the −200 m/s ejecta will be the main source. Phaethon itself crosses the Earth's orbit around 2224.

Prior to 2202 the trails are more than 0.002 AU from the Earth's orbit – too far to produce active meteor showers. High activity meteor showers are expected in 2203, 2206, 2207, 2209 and from 2211 to 2236 because in these years the trails approach to within 0.001 AU of the Earth. After 2237 the artificial meteor shower activity will tail off because of the increasing distance of the trails from the Earth's orbit.

2.2. Results: slow ejecta velocity of 20 m/s

Fig. 2 shows the evolution of a tube of the dust trail after the simulated impact event on 2022 April 12 (Kasuga et al., 2006b) when the ejecta velocity is an order of magnitude less than that studied in the previous section. Generally, trails' evolution are associated with the parent moving. Therefore,

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[1] β – the ratio of solar radiation pressure to solar gravity.

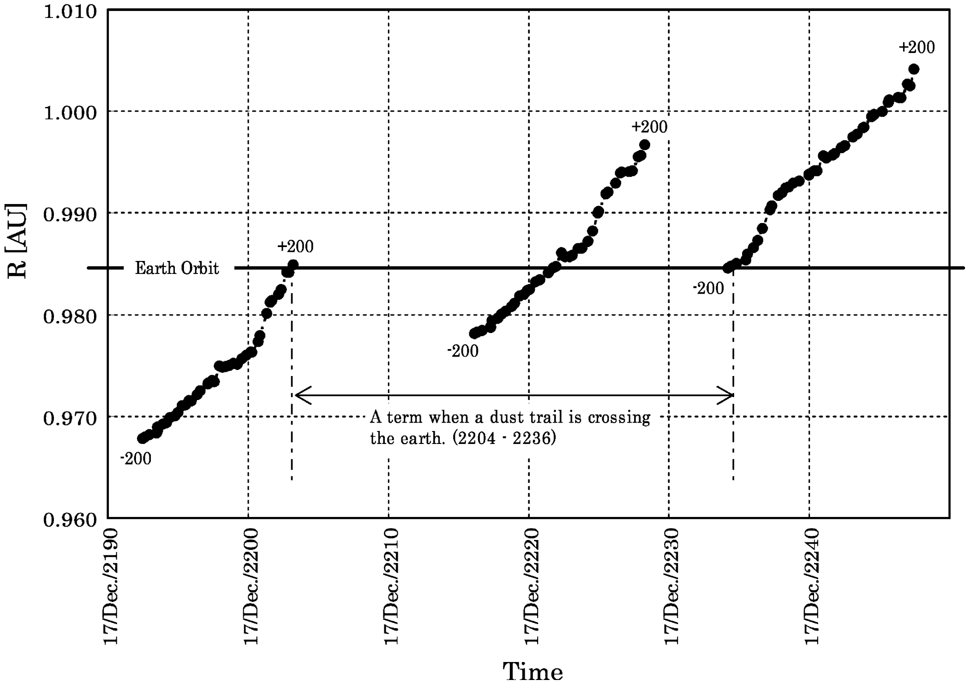

Fig. 1. Evolution of a tube of the dust trail after the impact event on 2022 April 12. '+200' (or '−200') is the ejection velocity (m/s) at impact. Artificial meteor showers would be seen between 2204 and 2236.

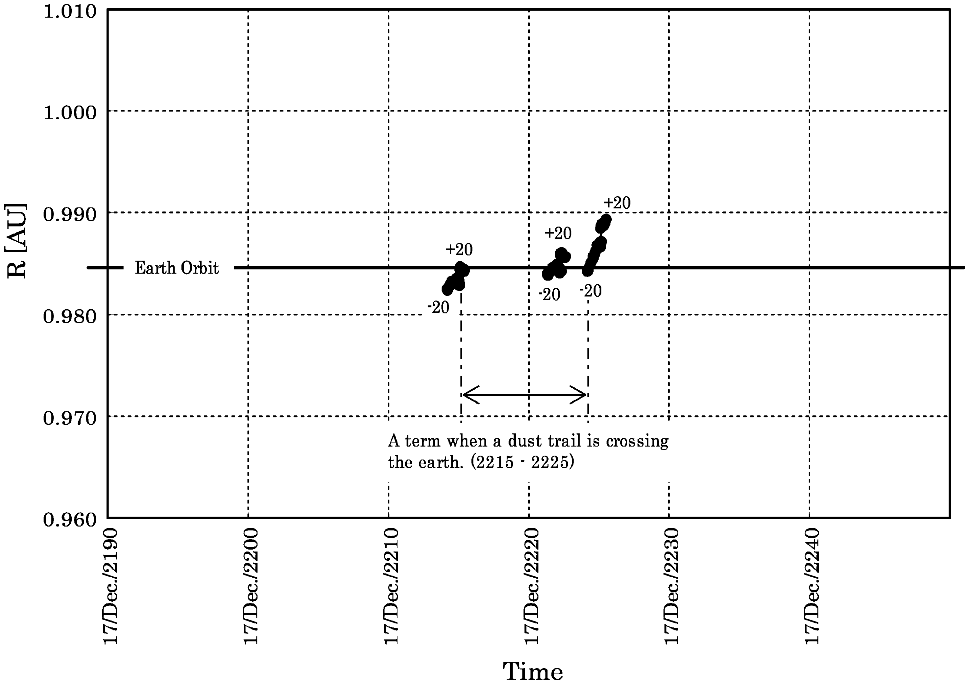

Fig. 2. Distribution of a tube of the dust trail after the simulated impact event on 2022 April 12. '+20' s(or '−20') is the ejection velocity (m/s) at impact. Meteor showers would be seen between 2215 and 2225.

ejecta velocities of meteoroids are applied to be ±20 m/s in Fig. 2. In this case, artificial meteor showers will occur over the 10 years from 2215 to 2225.

Prior to 2214 the trails are more than 0.002 AU from Earth's orbit. In 2218, 2219, 2222 and 2223, the trails approach within 0.001 AU of the Earth which implies particularly active meteor showers. After 2224 meteor shower activity will decrease due to the increasing distance of the trail from the Earth's orbit (above 0.002 AU).

3. Discussion

We investigated the production of artificial meteor shower and their dependence on the ejecta velocity at the impact for simulated impacts on 3200 Phaethon on 2022 April 12. If the ejecta velocities are of 200 m/s artificial meteor showers begin in 2204 and continue for about 30 years. If the ejecta velocities are only 20 m/s the artificial meteor showers last for only 10 years from 2215 to 2225. We conclude that the active period for artificial meteor shower tends to be sooner and last longer as the ejecta velocity gets faster.

If dust trails are to be the source of artificial meteor showers the size of ejected meteoroids needs to be larger than about a micron. During the DI collision on 9P/Tempel 1, micron sized dust particles were ejected and their released speed was relatively high (ranging from 100 to 300 m/s). Artificial activity triggered by the DI collision on 9P/Tempel 1 was small and did not last longer than normal activity level (Küppers et al., 2005).

Belton and A'Hearn (1999) suggested that the velocity and mass of an impactor should be above 33 km/s and 500 kg in order to penetrate the mantle of 3200 Phaethon and activate it like comet. To create a 33 km/s impact on 3200 Phaethon it is advantageous to select impact dates when 3200 Phaethon passes through the ecliptic plane on the Earth side for delivering substantial science payload with limited fuels. The DI collision on 9P/Tempel 1 would be expected to eject faster and larger meteoroids if the impactor had higher speed and mass (10 km/s and 370 kg, respectively) (A'Hearn et al., 2005). The production of an artificial meteor shower will require higher impact energy than that of DI on 9P/Tempel 1 (19 GJ) to artificially activate the target and produce higher speed ejecta and larger size meteoroids. In the future we will constrain the impact energy which relates the meteor shower activity rate and the period of artificially derived meteor showers.

Artificial Geminid meteors may be due to either evolved or fresh meteoroids liberated from surface or interior, respectively of 3200 Phaethon. Its surface appears to be rocky with an asteroidal, not comet-like, appearance (Green et al., 1985; Birkett et al., 1987) but it seems to have the evidence of once-cometary activity (Gustafson, 1989). Due to its small perihelion distance ($q \sim 0.14$ AU) thermal alteration of its surface is likely.

Kasuga et al. (2006a) investigated the thermal desorption of Na in meteoroids and its dependence on perihelion distance of meteor showers. Na is a relatively volatile and abundant element in meteoroids in meteor showers. Thus, Na is a good indicator for the effect of solar heating on meteoroids. Spectroscopic studies of Geminid meteors confirm a diversity of Na abundance, from extreme Na depletion to almost the solar abundance (e.g. Kasuga et al., 2005; Trigo-Rodrìguez et al., 2003). The wide range of Na abundance in Geminid meteors may be due to their history and position on the parent body before the meteoroids were ejected. Thermal desorption of Na in Geminid meteoroids while they are independently undergoing orbital evolution in interplanetary space is difficult because the temperature of meteoroids at $q \sim 0.14$ AU is lower than the sublimation temperature of alkali silicates (~900 K) (Kasuga et al., 2006a). Therefore, the diversity of Na abundances in Geminid meteors can only originate in the thermal evolution of 3200 Phaethon itself.

A DI-like collision on 3200 Phaethon would reveal the nature of dormant comets from both below and on the surface. Among other useful scientific studies, We may be able to better understand the puzzling variety of Na abundances in Geminid meteors.

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